

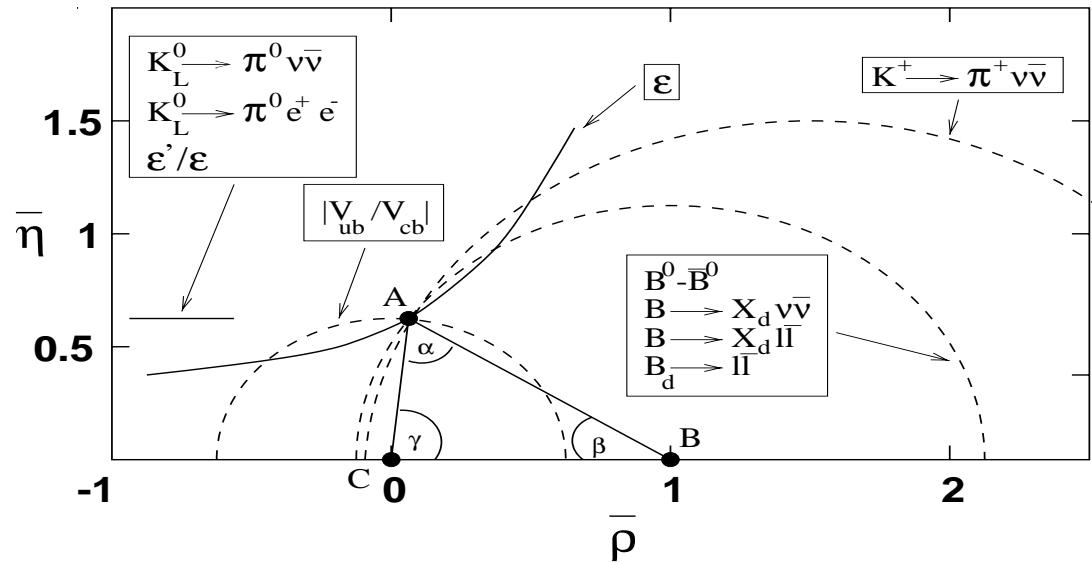
June 16, 2001  
CP2001 PISA

# Prospects for Measuring $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ at BNL



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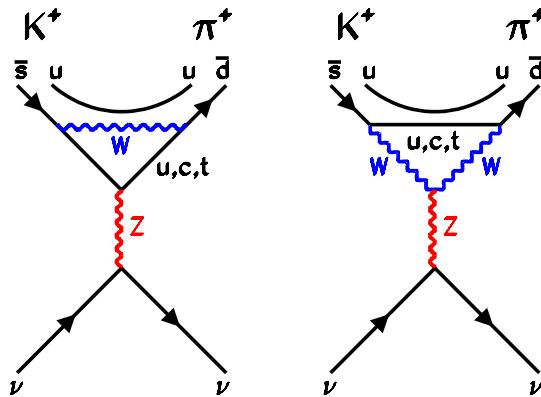
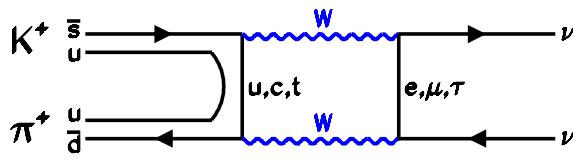
Unitarity relations e.g.  $V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} = 0$



Four "Super-clean" K and B physics inputs will test the SM CP-V picture. (Buras)

- |                                                                       |                             |
|-----------------------------------------------------------------------|-----------------------------|
| $K^+ \rightarrow \pi^+ \nu \bar{\nu}$                                 | E787/E949 (BNL), CKM (FNAL) |
| $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$                               | KOPIO (BNL), KAMI (FNAL)    |
| $B_d \rightarrow \Psi K_s$                                            | BABAR, BELLE, CDF, HERA-B   |
| $\frac{x_s}{x_d} = \frac{B_s - \overline{B}_s}{B_d - \overline{B}_d}$ | CDF, LEP, SLD, LHCb, BTEV   |

## $K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model



	$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$
Top Dependence	$ \lambda_t  =  V_{ts}^* V_{td} $	$\text{Im}(\lambda_t) = \text{Im}(V_{ts}^* V_{td})$
Calc. BR ( $10^{-10}$ )	$0.82 \pm 0.32$	$0.28 \pm 0.1$
Est. Theory Uncertainty	5% (charm)	1%

- Negligible long distance effects ( $10^{-13}$ ).
- Hadronic matrix elements from isospin analog  $K^+ \rightarrow \pi^0 e^+ \nu_e$ .

## **KOPIO Collaboration**

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†Subject to approval by INFN

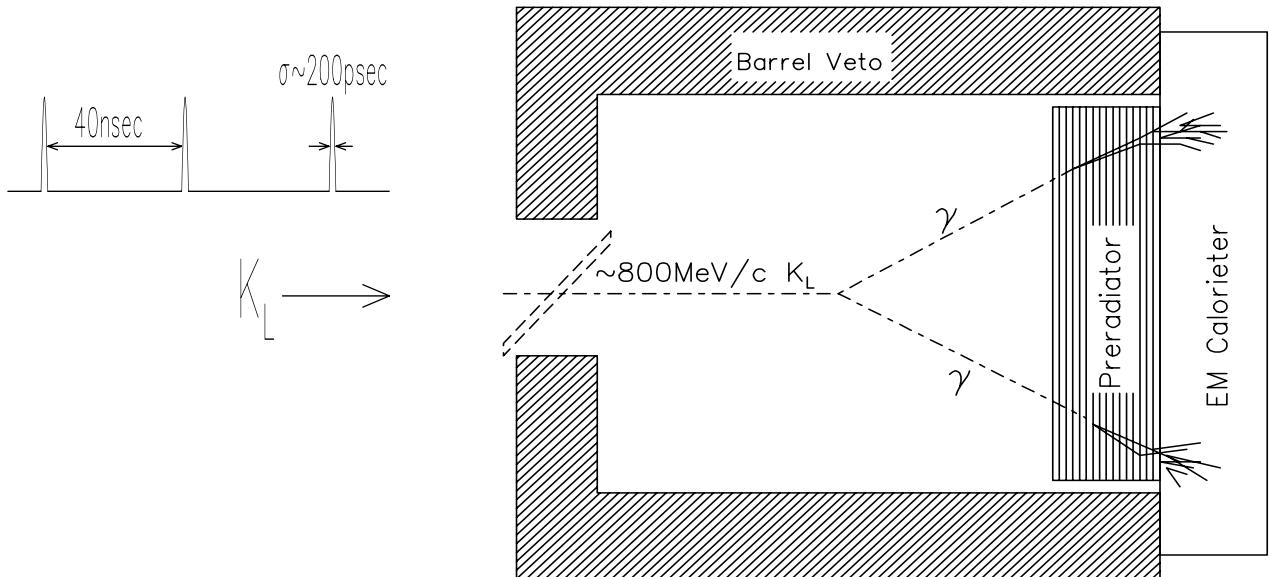
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# KOPIO: A Proposal to Measure $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Lessons from E787:

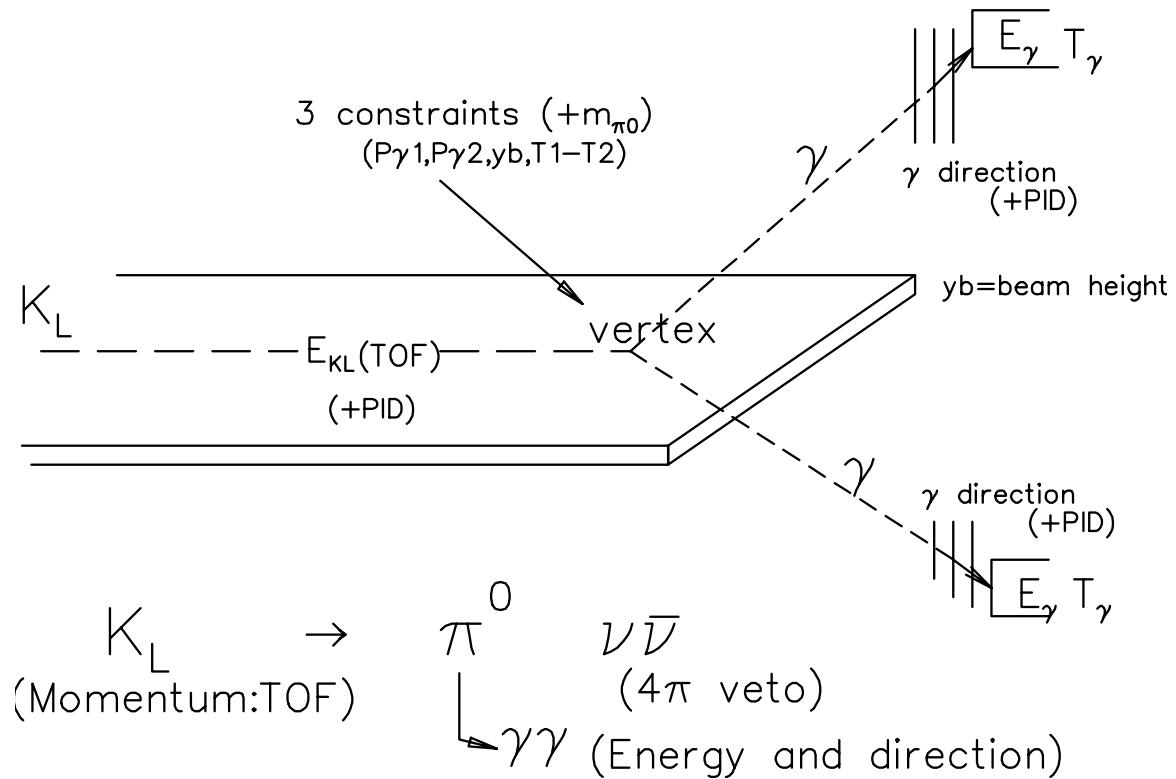
- Measure as much as possible:  
Energy, position and *ANGLE* of each photon.
- Work in the C.M. system :  
Use TOF to get the  $K_L^0$  momentum.
- Photon Veto limited by photonuclear interactions at low energies.



# Kinematics

Full kinematic reconstruction and particle identification

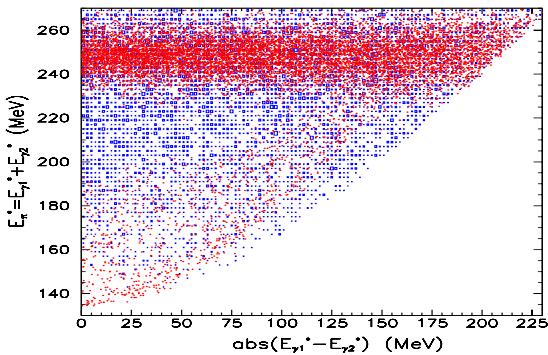
- Preradiator:  $\gamma$  direction, energy, PID item EM  
Calorimeter:  $\gamma$  energy
- RF bunched beam:  $K_L$  energy and PID
- Vertex reconst.:  $K_L$  direction (3 constraints)



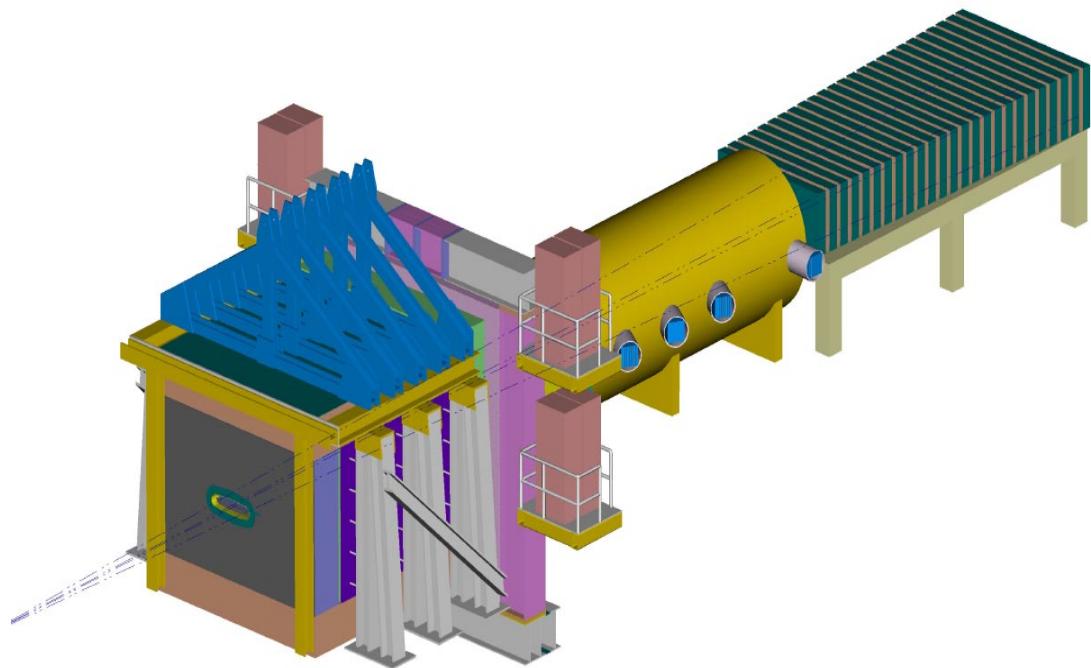
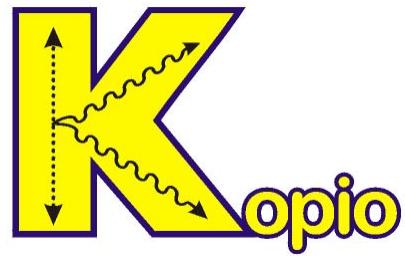
# KOPIO: Challenges and Goals

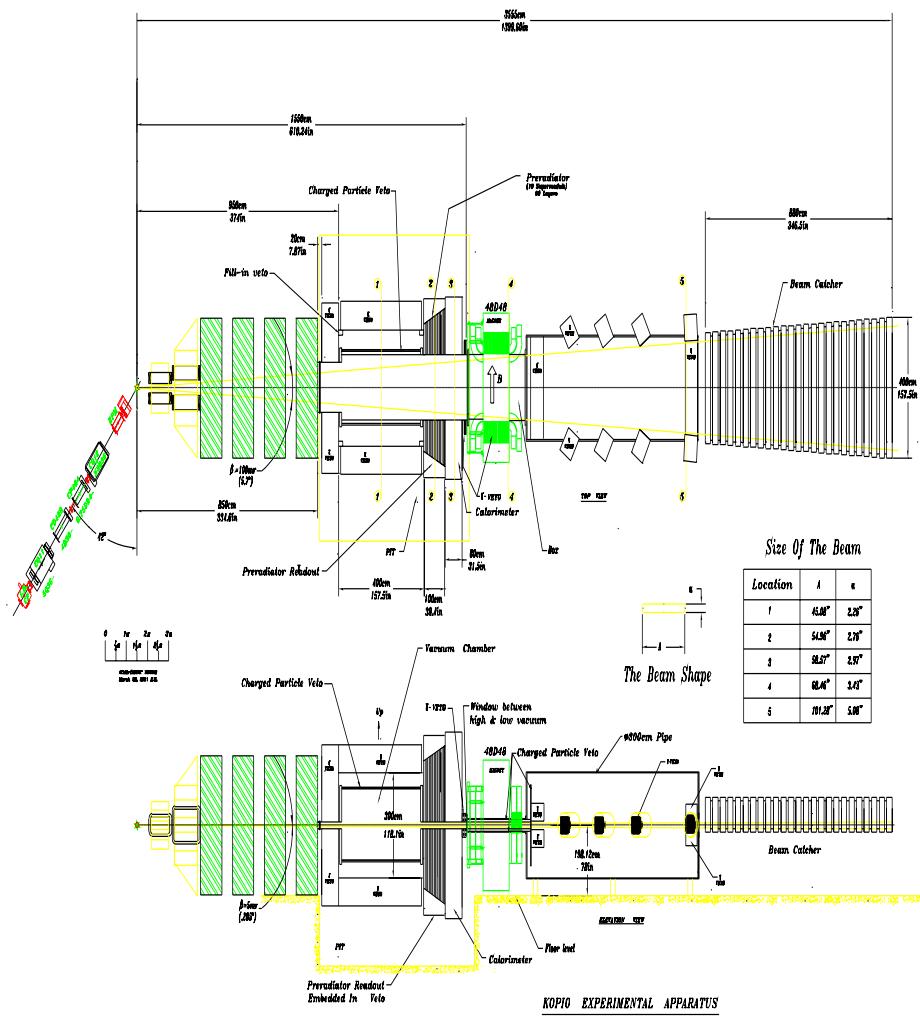
- Largest background source  $K_L^0 \rightarrow \pi^0\pi^0$ .  
Weapons: Kinematic reconstruction, photon veto.  
Eliminate events with missing low energy photons.
- Photon inefficiency :  $10^{-4}$  at 200 MeV.  
(Comparable to E787).
- Photon angular resolution : 17 mr at 350 MeV
- Energy resolution :  $\frac{2.7\%}{\sqrt{(E(GeV))}}$ .

$K_L^0 \rightarrow \pi^0\pi^0$  Background  
 $E_{\pi^0}^* \text{ vs. } |E_{\gamma 1}^* - E_{\gamma 2}^*|$



KOPIO GOAL: 50  $K_L^0 \rightarrow \pi^0\nu\bar{\nu}$  events with S/N=2.



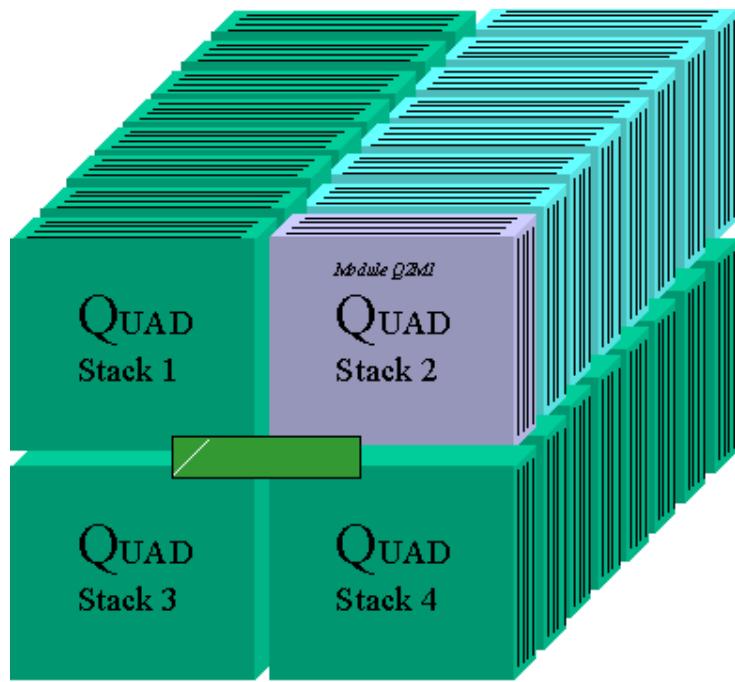
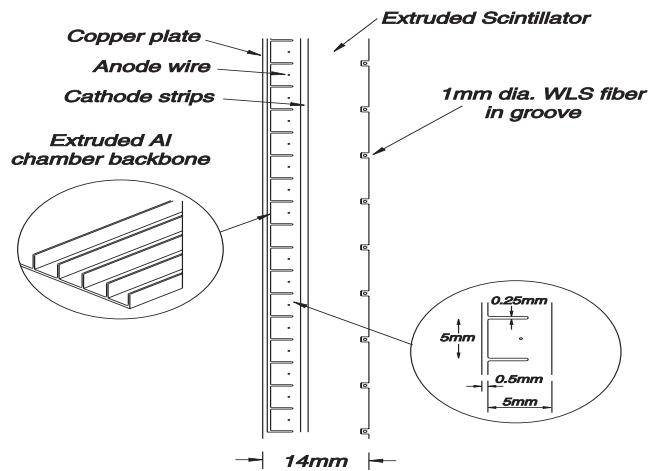


# PRERADIATOR

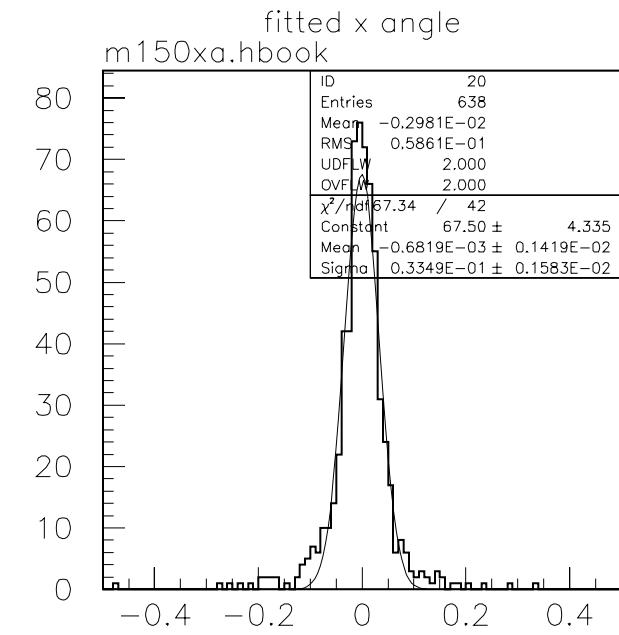
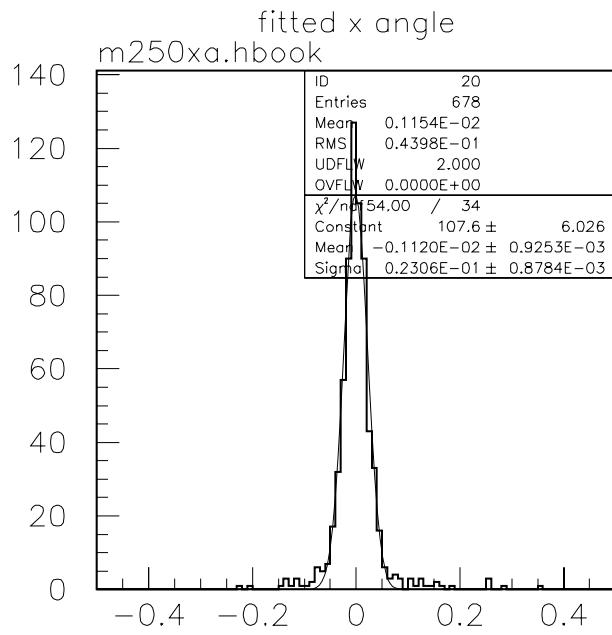
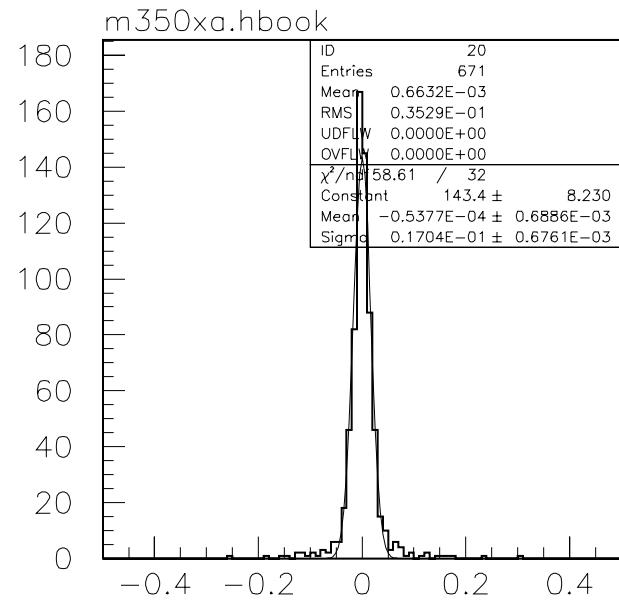
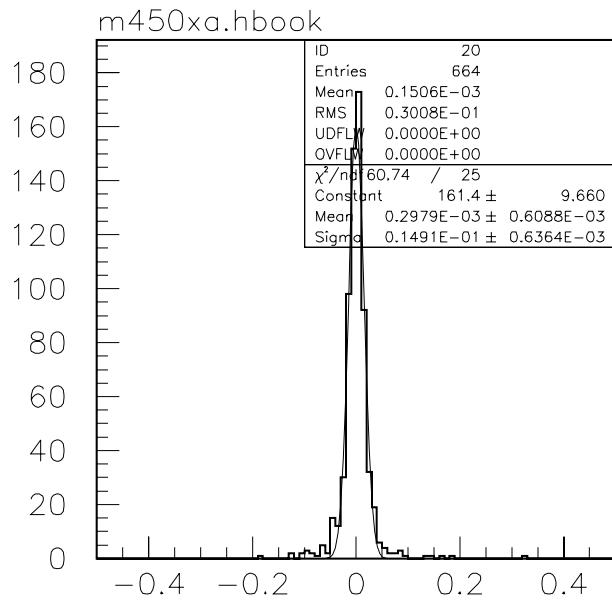
## Functions:

- Conversion efficiency:  $2 X_0$
- Angular resolution:
  - $0.034 X_0$  per layer/ 64 layers
  - 1.4 cm layer separation
  - $150 - 200 \mu m$  position resolution
- Energy resolution:  $1 - 2\% / \sqrt{E(GeV)}$
- Trigger - segmented scintillators

# PRERADIATOR DESIGN



# PRERADIATOR SIMULATION

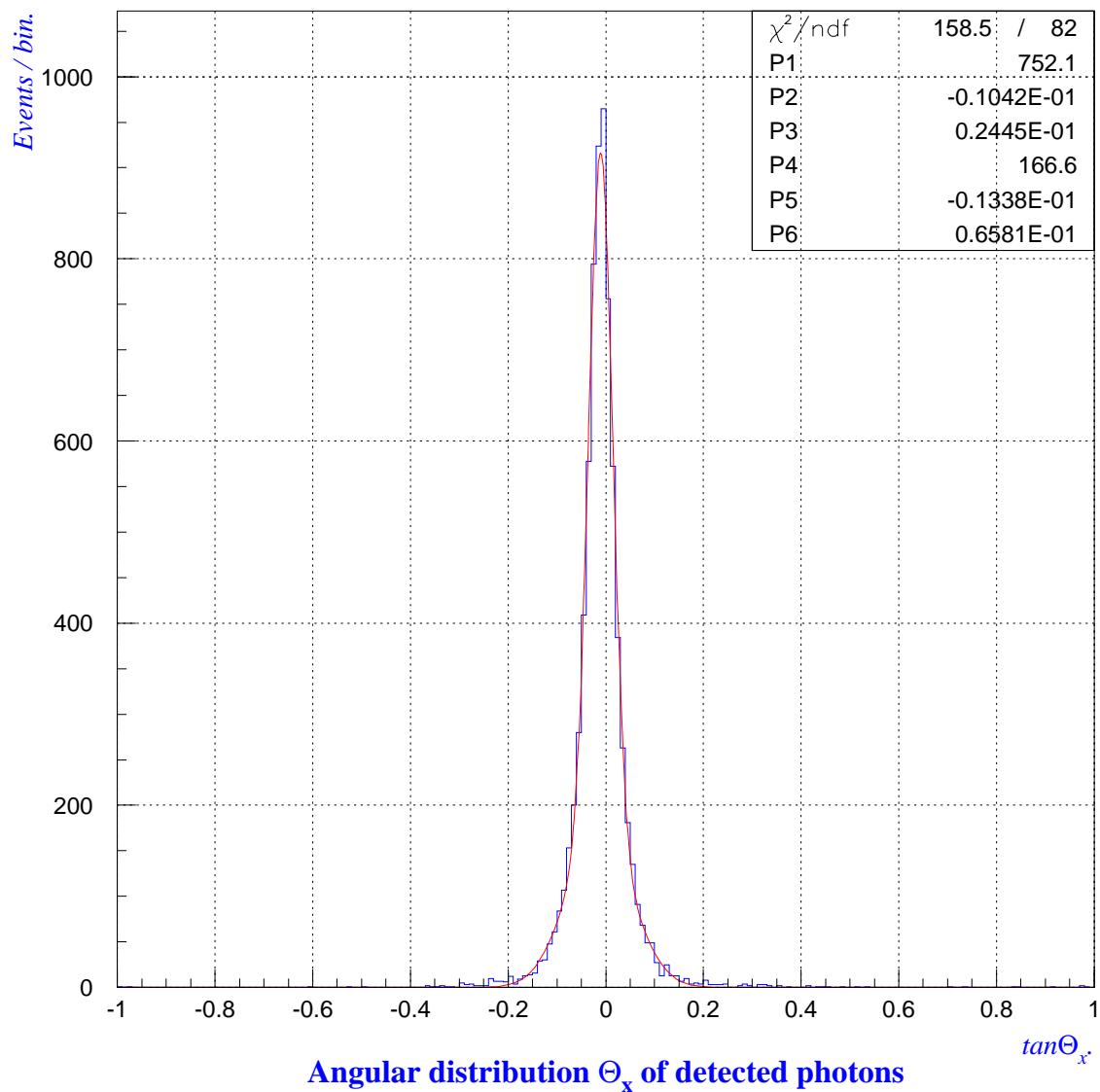


fitted x angle

fitted x angle

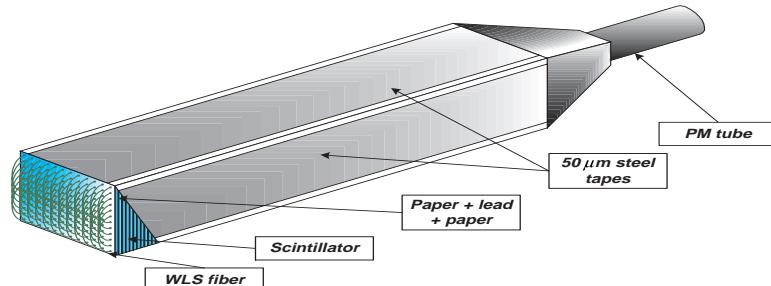
# Tagged Photon Test of Preradiator

KOPIO. Preradiator Prototype Test. Cathode readout.

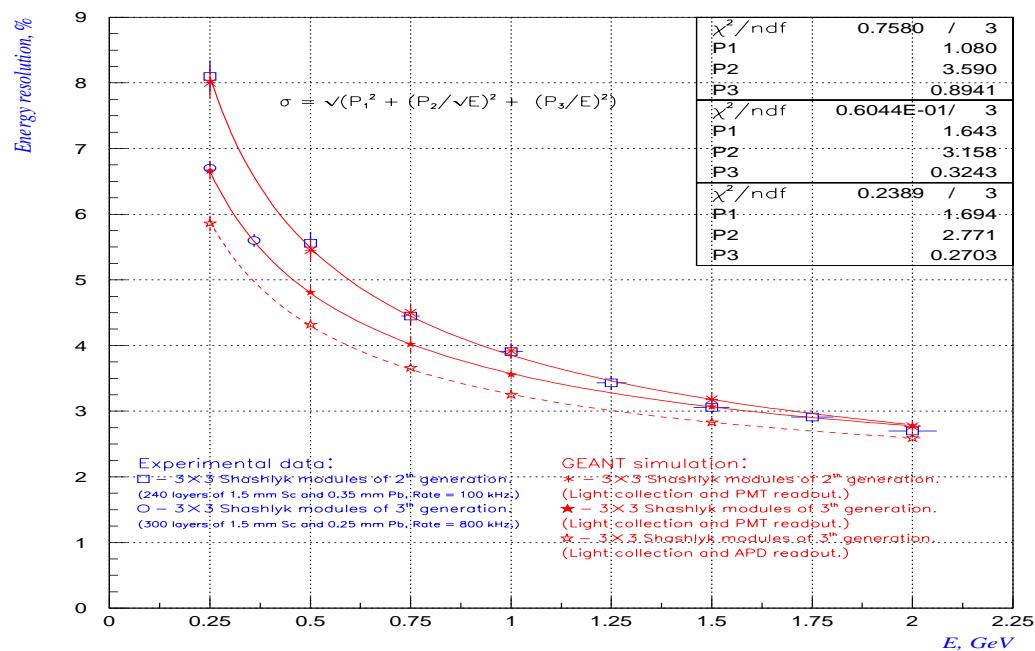


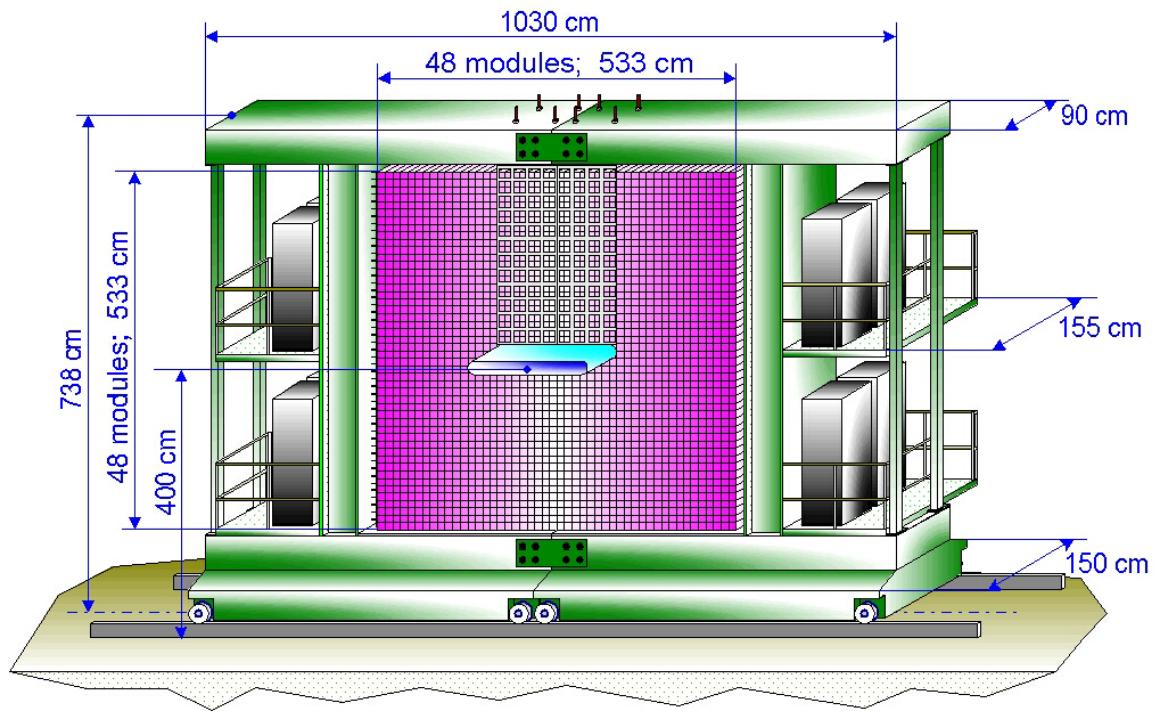
# SHASHLIK CALORIMETER

Expected Performance:  $\frac{\Delta E}{E} = \frac{3.0\%}{\sqrt{(E(GeV))}}.$



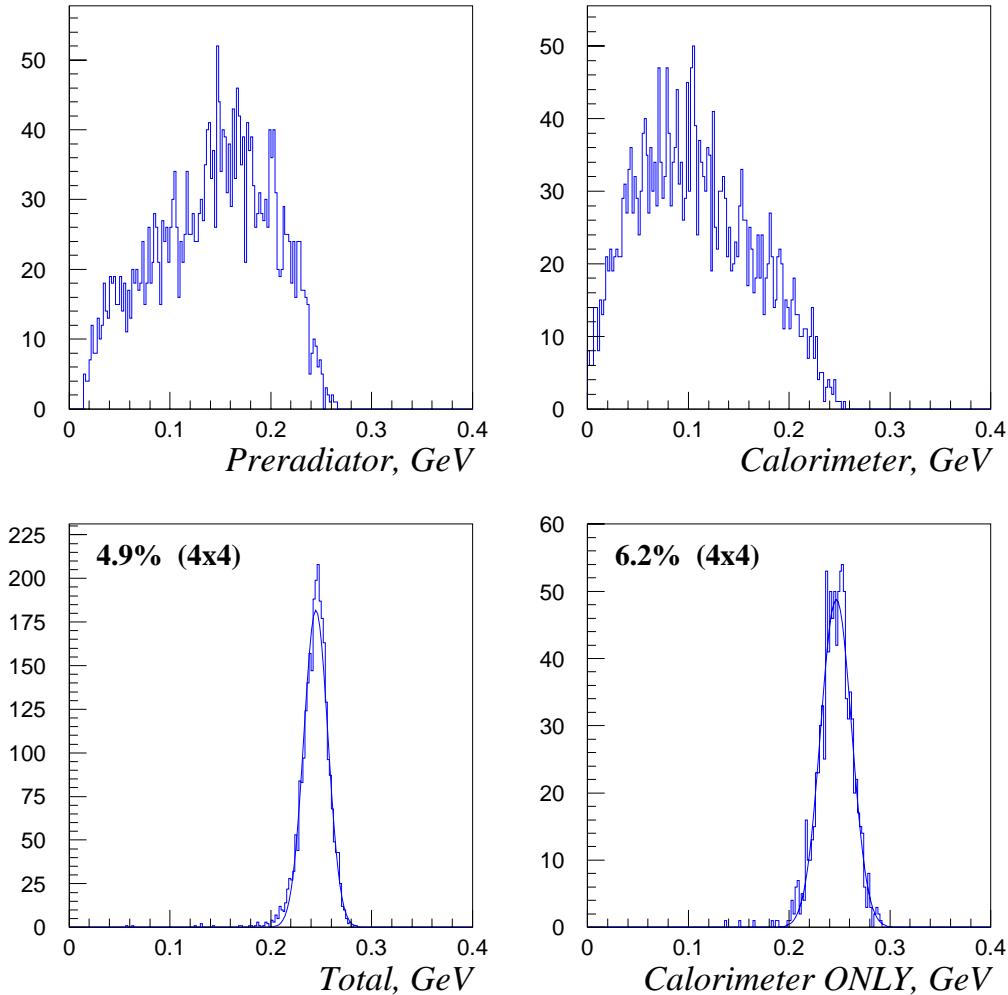
**KOPIO. Shashlyk Prototype Test. Gamma beam.**





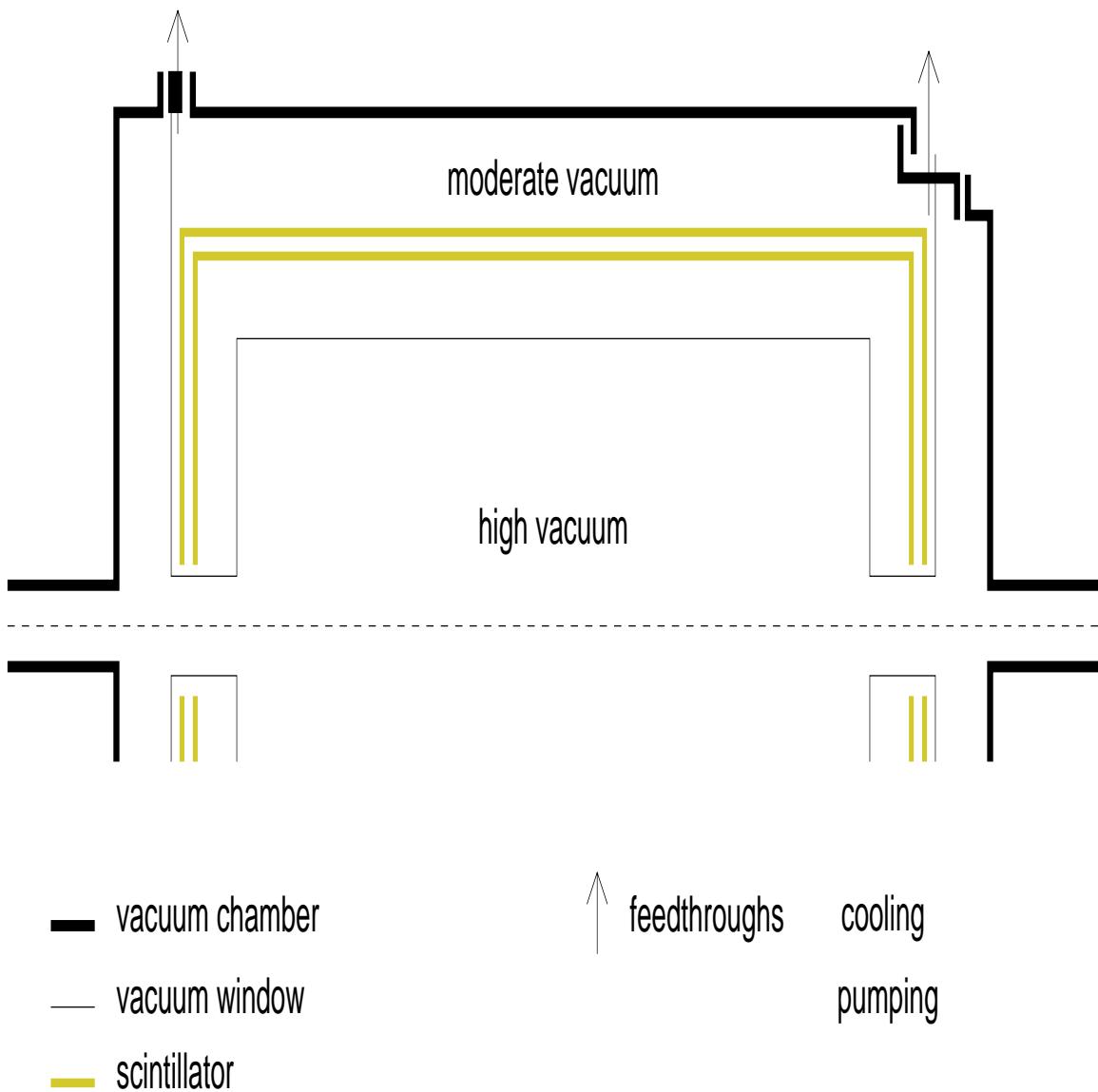
# Combined PR and Calorimeter Energy Measurement

KOPIO. 250 MeV photon in Preradiator and Calorimeter



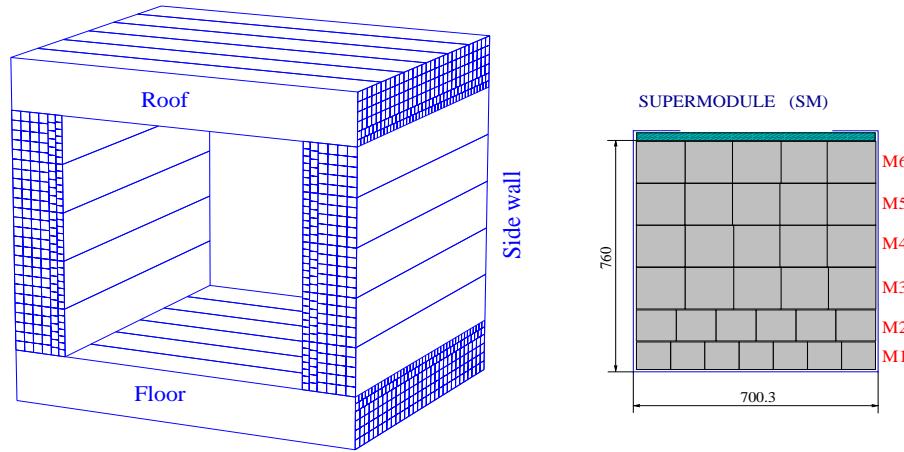
GEANT SIMULATION RESULTS:  $\frac{\sigma}{E} = \frac{2.5\%}{\sqrt{E(GeV)}}$

# Charge Particle Veto System

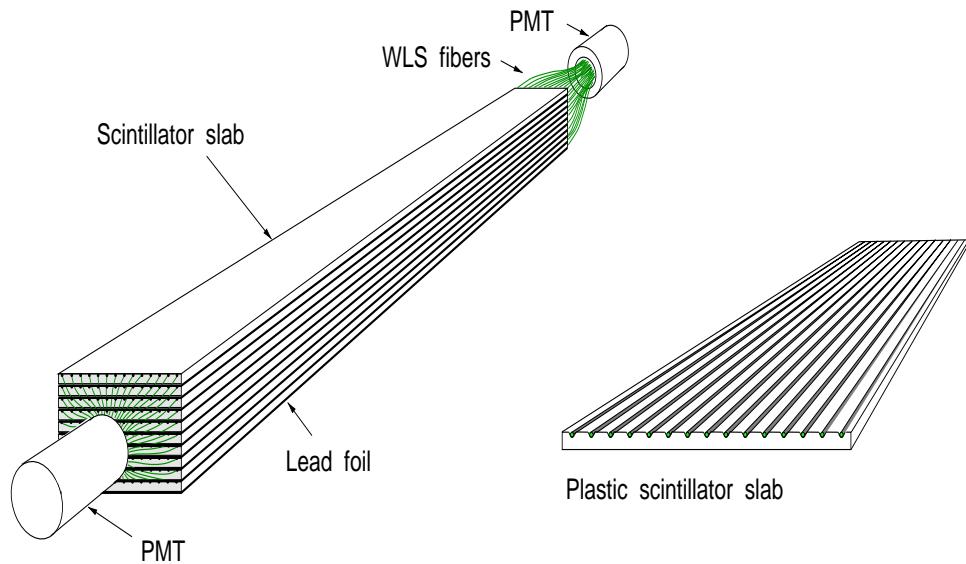


Estimated inefficiencies:  $10^{-4}$  for  $\pi^-$  and  $e^+$

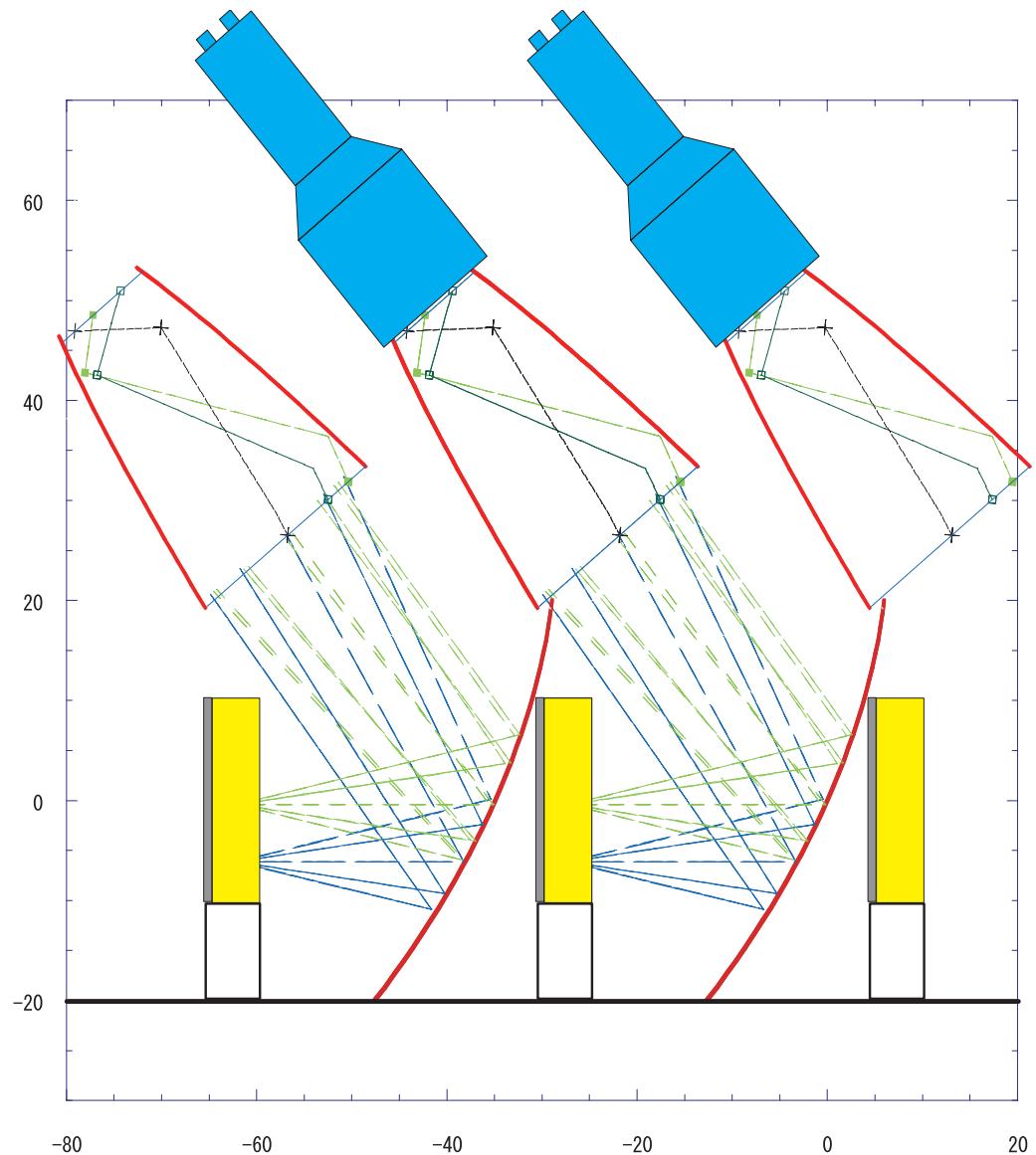
# Barrel Photon Veto System



Roof&floor SM size: 70x76x490 cm  
Side wall SM size : 70x76x420 cm

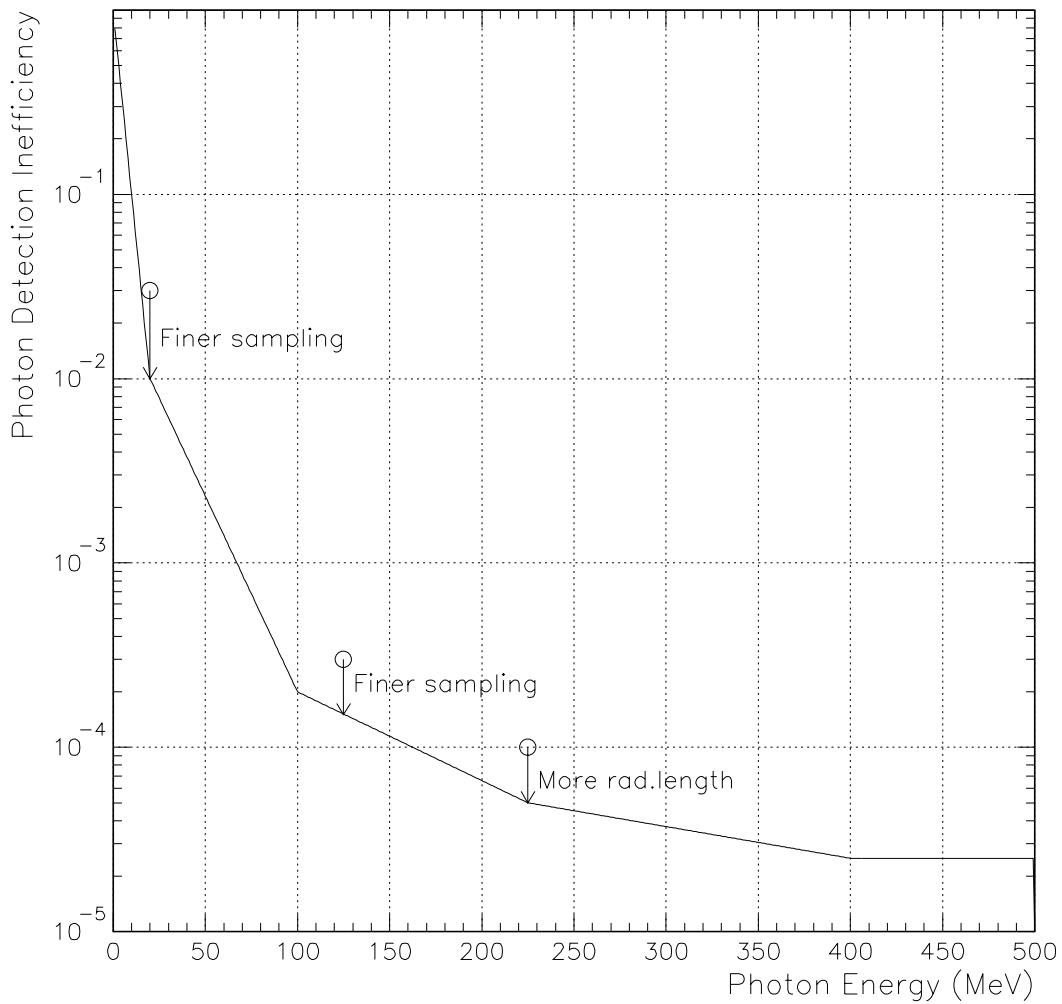


# Beam Catcher Detector



Pb radiators with Aerogel Cerenkov detectors

# Photon Detection Inefficiency



# KOPIO Photon Veto Capabilities

E787 measurements:

\*\* Low Energy ( 20-100MeV)  $\bar{\epsilon}_\gamma = 10^{-2}$

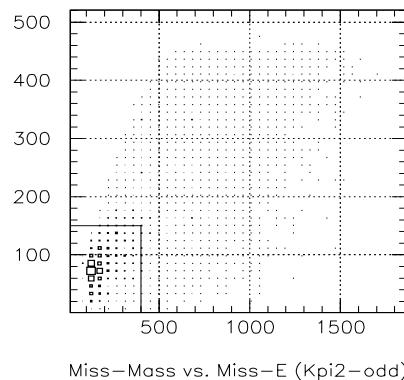
\*\* High energy (100-220MeV)  $\bar{\epsilon}_\gamma = 10^{-4}$

Kinematic suppression of low energy missing  $\gamma$ 's:

Missing mass ( $2E_1^{miss}E_2^{miss}\cos\theta_{12}$ ) vs.

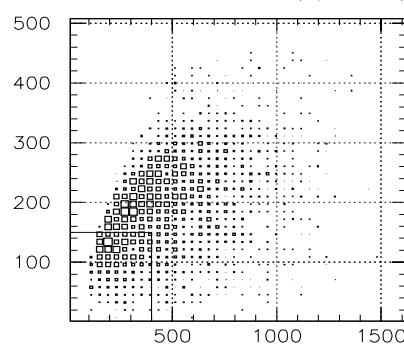
Missing energy ( $E_1^{miss} + E_2^{miss}$ )

$K_L \rightarrow \pi^0\pi^0$

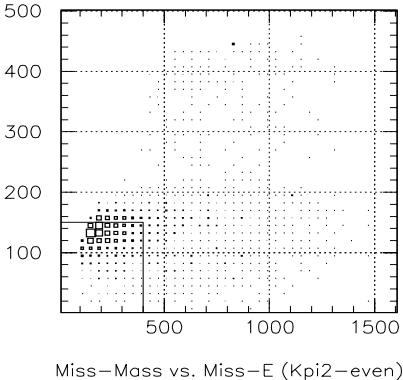


Miss-Mass vs. Miss-E (Kpi2-odd)

$K_L \rightarrow \pi^0\nu\bar{\nu}$



Miss-Mass vs. Miss-E (Kpi2-even)



Miss-Mass vs. Miss-E (pinn)

Overall  $\pi^0$  inefficiency:  $(10^{-4})^2 = 10^{-8}$

## Critical KOPIO Performance Requirements

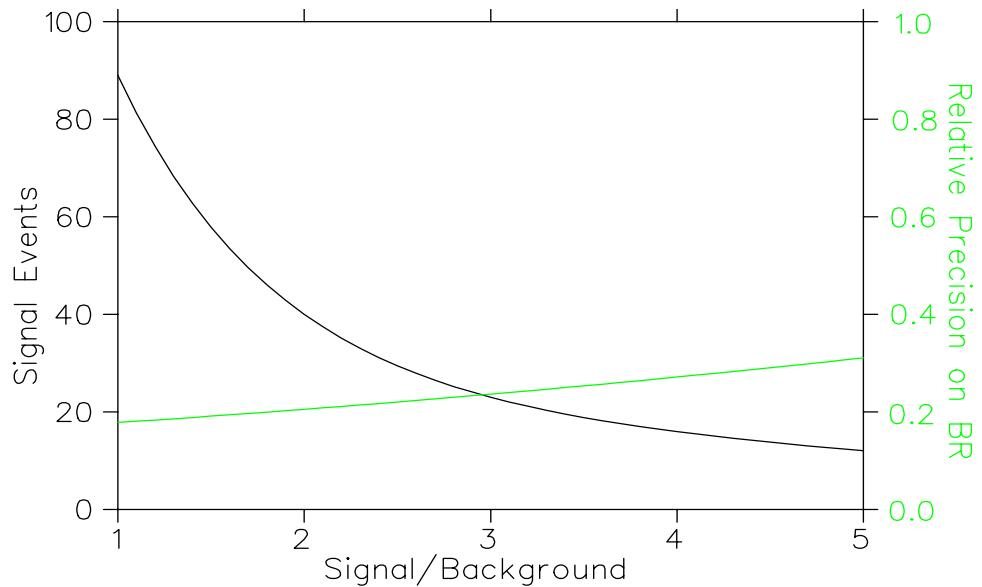
Parameter	Minimal Requirement	Expected Performance
$E_\gamma$ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
$\theta_\gamma$ resolution (250MeV)	$(25 - 30) \text{ mr}$	23 mr
$t_\gamma$ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
$x_\gamma, y_\gamma$ resolution(250MeV)	10mm	< 1mm
$\mu$ -bunch width	300ps	200ps
$\gamma$ -veto inefficiency	$\bar{\epsilon}_{E787}$	$0.3\bar{\epsilon}_{E787}$

ALL CRITICAL PARAMETERS HAVE BEEN ESTABLISHED BY TEST MEASUREMENTS

# KOPIO Signal and Backgrounds

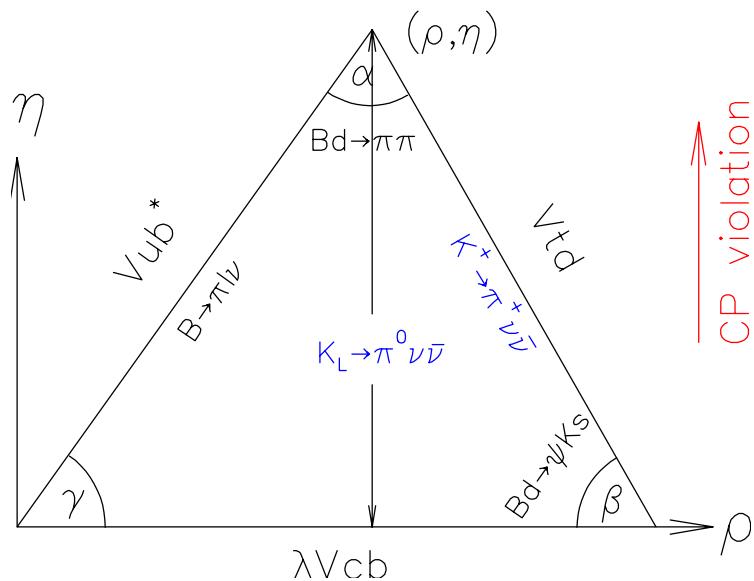
Process	Modes	Main source	Events
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$			40
$K_L$ decays ( $\bar{\gamma}$ )	$\pi^0 \pi^0, \pi^0 \pi^0 \pi^0, \pi^0 \gamma \gamma$	$\pi^0 \pi^0$	12.4
$K_L \rightarrow \pi^+ \pi^- \pi^0$			1.7
$K_L \rightarrow \gamma \gamma$			0.02
$K_L$ decays ( $\overline{\text{charge}}$ )	$\pi^\pm e^\mp \nu, \pi^\pm \mu^\mp \nu, \pi^+ \pi^-$	$\pi^- e^+ \nu$	0.02
$K_L$ decays ( $\bar{\gamma}, \overline{\text{charge}}$ )	$\pi^\pm l^\mp \nu \gamma, \pi^\pm l^\mp \nu \pi^0, \pi^+ \pi^- \gamma$	$\pi^- e^+ \nu \gamma$	4.5
Other particle decays	$\Lambda \rightarrow \pi^0 n, K_{\pi 2}^-, \Sigma^+ \rightarrow \pi^0 p$	$\Lambda \rightarrow \pi^0 n$	0.01
Interactions	$n, K_L, \gamma$	$n \rightarrow \pi^0$	0.2
Accidentals	$n, K_L, \gamma$	$n, K_L, \gamma$	0.6
Total Background			19.5

## Signal Events vs. S/N



# SUMMARY

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$  and  $K_L \rightarrow \pi^0 \nu \bar{\nu}$  offer unique opportunities to explore SM physics and search for non-SM effects.



E787→E949: heading below SM predictions

- E787 95-97 combined data still has one event!
- E787 -98 data will reach about  $0.8 \times 10^{-10}$
- E949 aimed at  $\leq 10^{-11}$  or 5-10 SM events

$$\underline{K_L^0 \rightarrow \pi^0 \nu \bar{\nu}}$$

A direct window into CP violation.

- Best way to determine  $\eta$
- Complementary to B system - compare results to search for new physics.

## KOPIO

- Goal: 50 “SM” events
- Low background
- $\sim 10\%$  measurement of  $Im\lambda_t$ .
- Explore from  $10^{-8}$  down to  $\sim 10^{-12}$

**KOPIO:** exploits special conditions at the AGS

- Proton intensity  $10^{14}$ /pulse, micro-bunching
- Highly effective constraints and cross-checks
- Experience of recent AGS exps.

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$  (E787): vetoes, electronics, analysis

$K^+ \rightarrow \pi^+ \mu e$  (E865): rates, calorimetry